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Simulation of Puget Sound hydrography and circulation, Spring - Summer 2004

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University of Washington's PRISM project (http://www.prism.washington.edu/science/marine/modeling.html), with support from National Oceanographic Partnership Program, has been operating a computer model of circulation for the entire Puget Sound (http://tima.ocean.washington.edu). This is a higher resolution version of the model reported in a previous Puget Sound Research Conference (Kawase, 1998). The model is based on the Princeton Ocean Model (Blumberg and Mellor, 1987), and represents the Puget Sound basin at a cell resolution of 360 meters in the east-west direction and 540 meters in the north-south direction and with fourteen vertical levels in a bathymetry-following (sigma) coordinate. The model receives meteorological forcing from the high resolution operational weather prediction system of the Northwest Regional Modeling Consortium (http://www.atmos.washington.edu/mm5rt/); freshwater forcing from the USGS real-time river gauge data, augmented by a statistical model for ungauged rivers (Lincoln, 1977); and synthetic tidal forcing and climatological hydrographic conditions on an open boundary in the eastern Strait of Juan de Fuca.

The equations for the model are those of the standard primitive equation (hydrostatic) dynamics. Given initial and boundary conditions, the model calculates over discrete time-steps the sea surface elevation, three components of circulation velocity, temperature, salinity, and parameters pertaining to turbulent mixing. The model has been run in a daily hindcast mode since March 11, 2004. Comparison of the modeled hydrography with data collected over this period indicates that, while the modeled salinity field has a reasonable range of values, the seasonal cycle of temperature is exaggerated. The model is generally too cold at the beginning of the hindcast period and becomes too warm by July – August, with the anomaly persisting into the fall (Figure 1). This appears to be due to a lack of seasonal cycle in outgoing l... rface of the Sound, for which no good data exist and the n

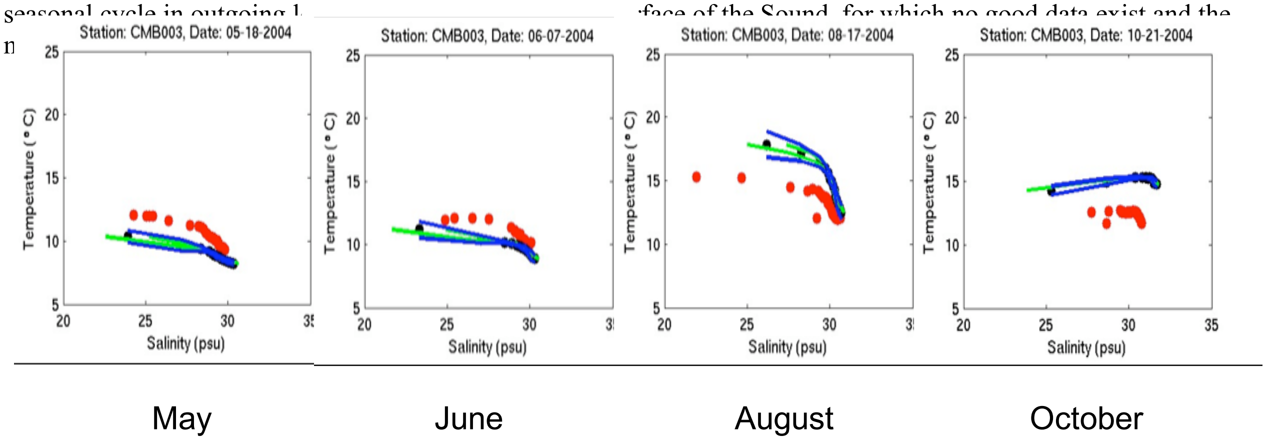

Figure 1. Salinity vs. temperature in Commencement Bay: modeled (blue-green, showing range over tidal cycle) and observed (red). Data from Washington State Department of Ecology's monthly monitoring program.

The model has been providing useful insights into the workings of Puget Sound in various locations. Currently, the model is used in support of Hood Canal Dissolved Oxygen Program (HCDOP) for hypothesis generation and field work planning. Analysis of the modeled field indicate that, in the first half of 2004, Hood Canal had a three-layer circulation, with outflow at the surface, inflow at mid-depths and weak outflow at the bottom (Fig. 2). The currents had weak intensification towards Kitsap Peninsula. This pattern of circulation is typical of a period during which a layer of dense bottom water prevents fresh inflow reaching the bottom (Ebbesmeyer *et al.,* 1989), and is in agreement with hydrographic data collected over this period (J. Newton and M. Warner, pers. comm.).

Variability in both hydrographic quantities and currents is primarily due to tides, but superimposed on it is a longer-period variability pronounced near the surface (Fig. 3). Removing tides through regression reveals this variability to be coherent with wind over the Canal (Fig. 4). During a northerly (southward) wind event, the near-surface layer of the southern Hood Canal becomes anomalously fresh, which can be interpreted as due to a pile-up of the fresh surface water at the head of the Canal resulting in downwelling and pushing-down of the pycnocline. This interpretation is supported by the changes seen in the velocity field, which show a southward velocity anomaly in the surface layer and a northward anomaly in the layer below. This is a characteristic response of a stratified channel to an applied along-channel wind stress, and similar behavior is seen in the Main Basin of Puget Sound (Bretschneider *et al.*, 1985; Matsuura and Cannon, 1997).

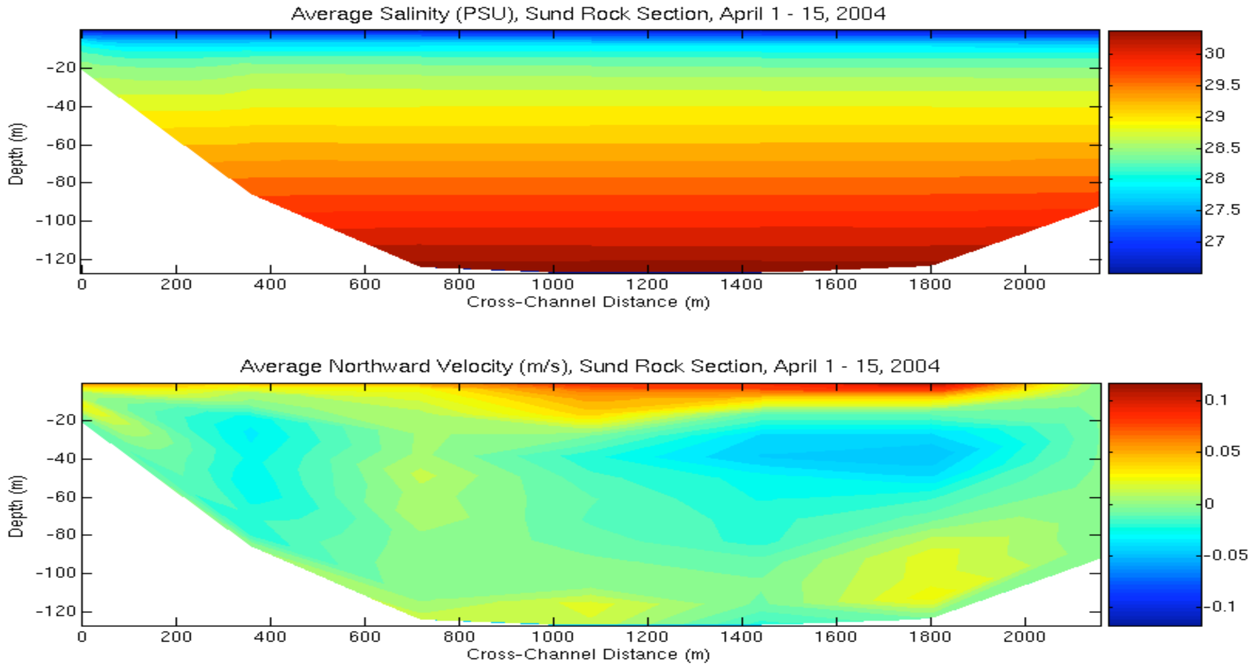

Figure 2. Cross-sections of average model salinity (PSU) and northward velocity (meters per second) in southern Hood Canal off Sund Rock.

Conversely, during a southerly (northward) wind event the surface layer becomes anomalously salty, and a northward velocity anomaly in the surface layer develops (Fig. 4). A northward wind would push the surface layer

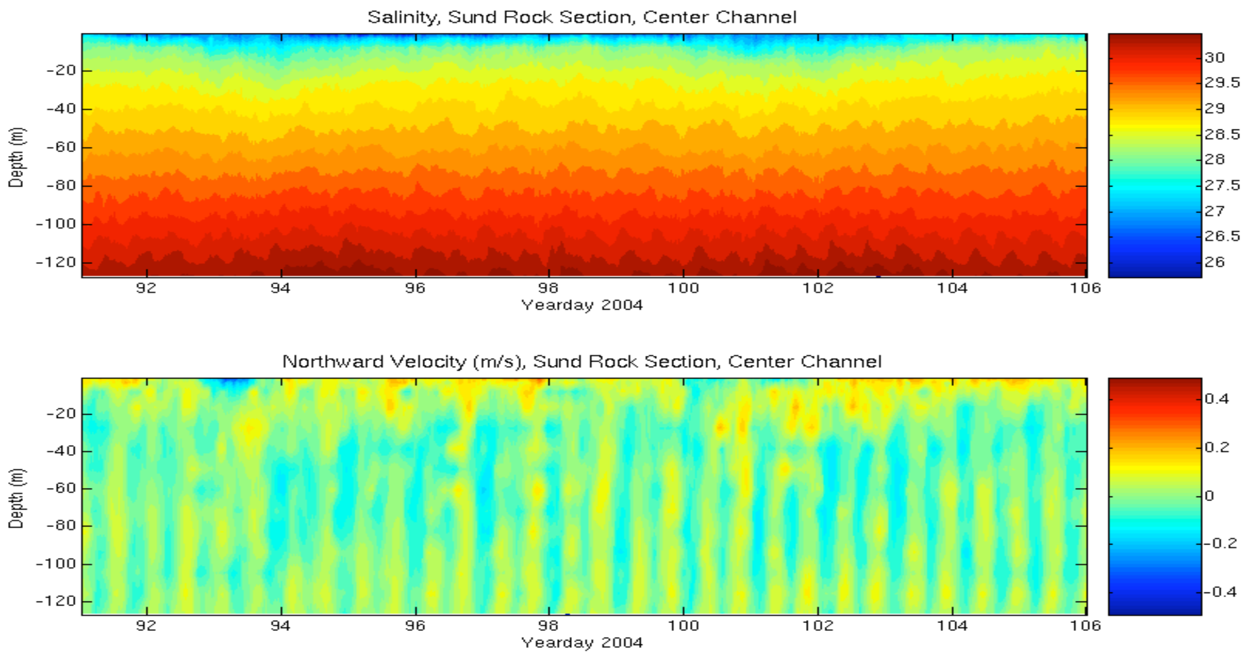

Figure 3. Modeled salinity (PSU) and northward velocity (meters per second) over a spring-neap cycle in April 2004, at a center channel location off Sund Rock.

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along and cause it to evacuate the head of the Canal; this would be compensated by upwelling of deeper layer waters, and a positive salinity anomaly would develop. Near-surface salinity variation does not seem coherent with precipitation, indicating that it is primarily wind-driven (Fig. 4).

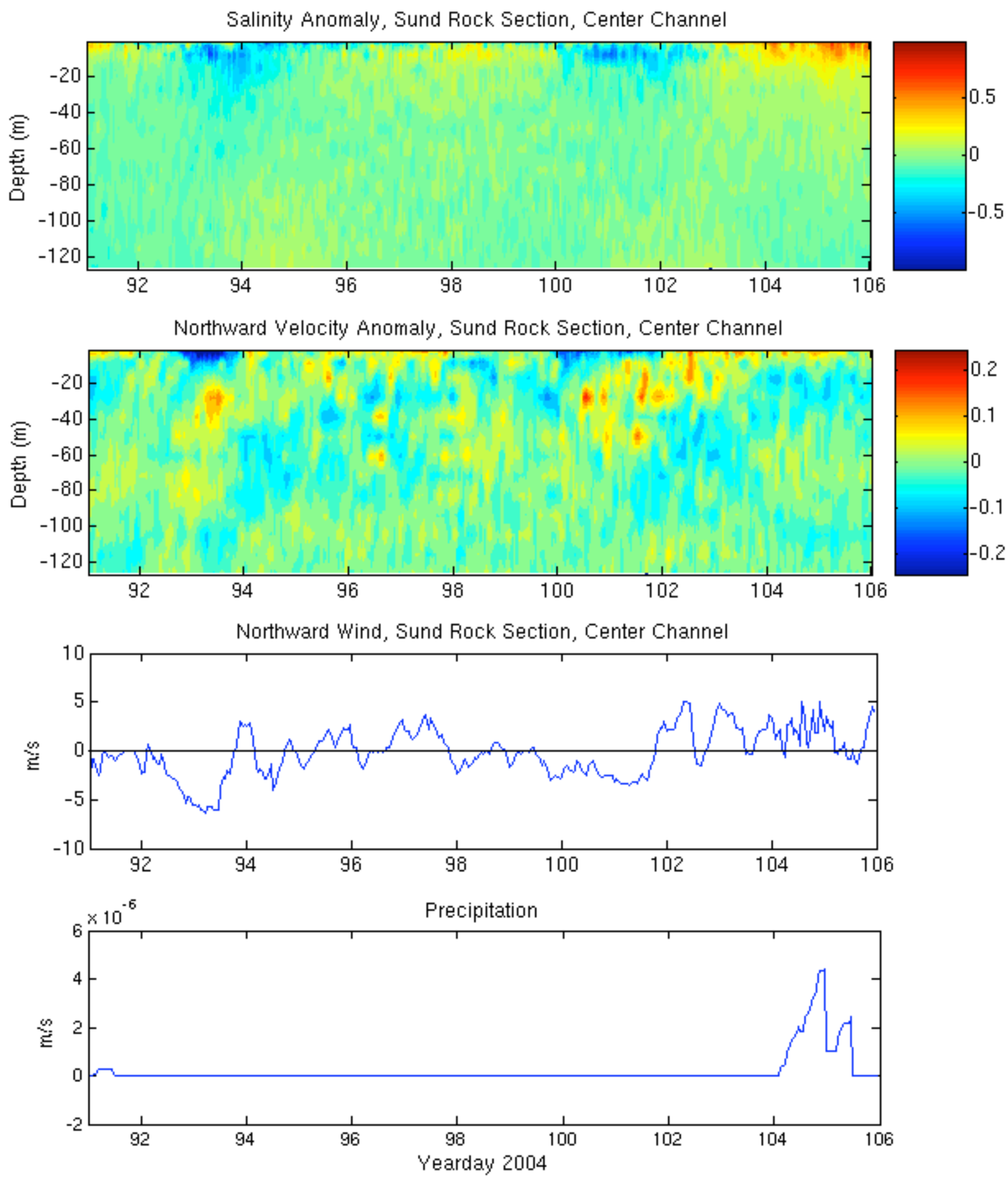

Figure 4. De-meaned and de-tided salinity and velocity at the center channel location off Sund Rock, in comparison with the northward wind speed and local precipitaion used as forcing for the model.

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Such wind-driven migration of the surface layer would cause the layer to evacuate parts of the canal, and its place would be filled with water upwelling from the depth. Because the upwelled water is also low in oxygen, wind-driven upwelling could be an important mechanism controlling oxygen concentration in near-surface waters of Hood Canal. There are indications that fish kill events are triggered by a southerly wind event, which would cause upwelling at the head of the Canal. Patterns of surface layer migration and resultant upwelling in the model can be highlighted by plotting positive salinity anomalies over a period of a wind event (Fig.5). During a northerly wind event, greatest salinity anomalies in the Canal are seen along Kitsap Peninsula north of Holly. This could best be interpreted as due to a cross-channel migration of a fresh water plume from Hamma Hamma River, which would normally take up this position. (The wind also affects the Hamma Hamma plume directly at the source, causing an anomaly bullet off the mouth of the river.) Weaker anomalies are seen along the Kitsap coast south of Chinom Point, and at the head of

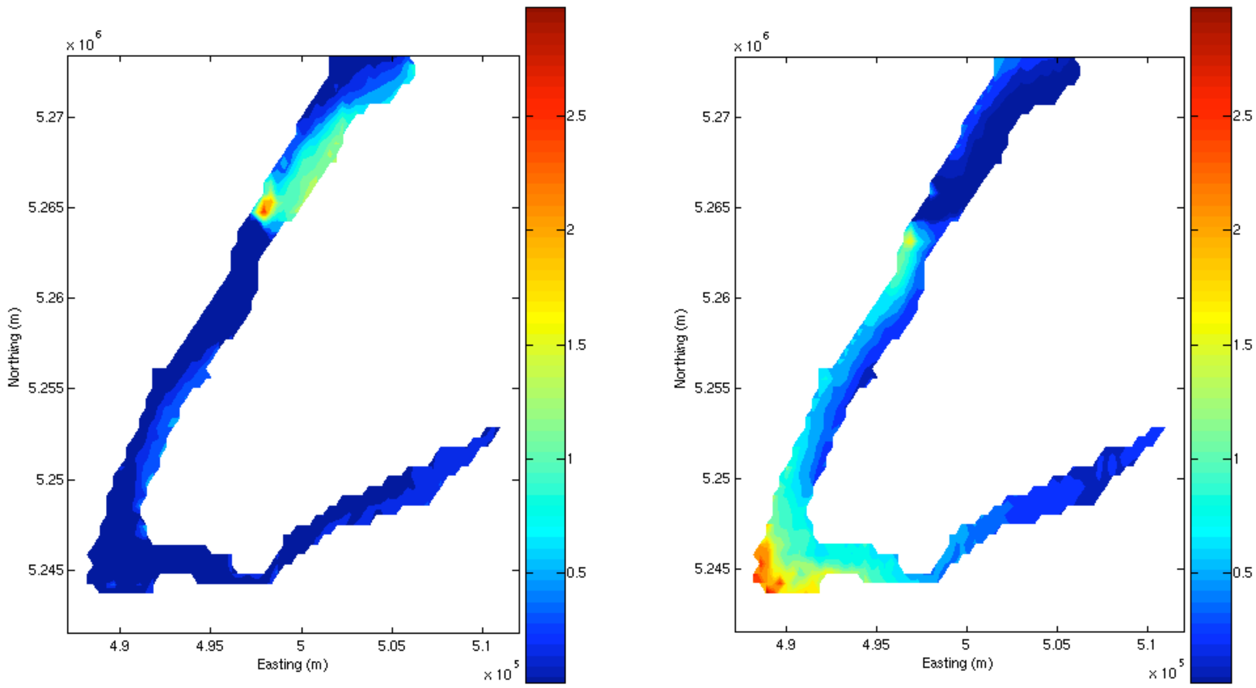

Figure 5. Positive anomalies in modeled salinity at the surface (PSU) averaged over a northerly (left) and a southerly (right) wind event. Only positive anomalies, indicative of upwelling, are highlighted.

Lynch Cove.

During a southerly wind event, strong positive salinity anomalies are seen at the head of the Canal in Annas Bay (Fig. 5), and a positive anomaly extends into the western half of Lynch Cove. Clearly this is a signature of the fresh water plume from Skokomish River being blown down the Canal by the wind. A positive anomaly also extends along the Olympic coast up to the mouth of Hamma Hamma River; the southern portion of this coastline is where fish kills are often reported. Weaker anomalies are seen along the Olympic peninsula further north and in much of Lynch Cove.

The cross-channel asymmetry of the upwelling pattern, with the northerly wind favoring the Kitsap side and the southerly wind the Olympic side, is indicative of an influence of earth’s rotation on the movement of the surface layer in response to the wind. Coriolis force acting on a moving surface layer would tend to deflect its motion to the right in the northern hemisphere; in a steady state this would result in an Ekman transport, where the surface water movement would be ninety degrees to the right of the direction of the wind. The Ekman tendency would cause the surface layer to move away from the Kitsap coast and towards the Olympic coast during a northerly wind event, and vice versa during a southerly wind event. The resultant upwelling pattern would favor the Kitsap side during a northerly wind event and the Olympic side during a southerly wind event, as modeled.

Since oxygen concentration in the subsurface waters of the Canal decreases towards the head of the Canal, upwelling at the head would have more adverse impact on the near-surface biota than upwelling closer to the mouth; it is reasonable to hypothesize that fish kill events can be caused by southerly wind events that push the surface layer towards the sea and cause upwelling at the head of the Canal.

The model displays a dynamically reasonable behavior at intraseasonal timescales, and is a helpful resource in investigating hypotheses and planning observational strategies. In particular, the model points to the importance of wind forcing in the dynamics of time-dependent circulation in Hood Canal. Quantitative verification of the model must await availability of more observational data from the Canal; as well, the model's problems over longer time scales indicate that better data, both for forcing and verification, are needed for the model study to move ahead.

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